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ENGINE KNOCK AND COMBUSTION CHAMBER FORM

By Karl Zinner

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By Karl Zinner

The development of internal combustion engines with independent ignition to the modern high-speed engines is closely allied with knocking. There have not been many changes in operating cycle, nor in the method of transforming chemical fuel energy through heat into motion energy, since Otto's day.

Ever since the fuel-air mixture introduced into the cylinder has been compressed by the piston prior to ignition, and since that time it has been proved in practice that the power and efficiency of this method are directly associated with the degree of precompression. The degree of precompression finds a limit in the knock with its concomitant high mechanical and thermal stresses. While at the beginning this limit had been tacitly accepted, the research work and development during the past twenty years has been directed toward pushing this limit further so as to be able to raise the power and the efficiency with the precompression (reference 1).

In this connection, one of the most significant discoveries was that, during the change from normal combustion, characterized by a moderate rate of advance of the flame front from the igniting source, to knocking combustion, the processes in the portion of the mixture burned last were responsible for the knock. It was possible to prove that the knocking consisted of a sudden rise of combustion speed to a multiple of the normal speed, which suggested a dissimilar combustion characteristic from that of the flame propagation. Without requiring at first a correct explanation of the underlying causes of this explosive combustion nor a better knowledge of processes involved, the concept that it depends upon the state of the last part of the charge to burn, "the residual charge," has proved extremely fruitful for the development of the Otto

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cycle engine. It seems obvious that the process of knocking depends on the pressure and temperature which the mixture, as yet untouched by the flame front, can sustain without itself becoming ignited, i.e., on the structure of the fuel itself and on the the opportunity the mixture has of absorbing this temperature from the walls and the advancing flame front. In connection with these views, the attempts to prevent knocking were chiefly centered on

1. The fuel,

2. The mixture distribution,

3. The combustion chamber shape.

The greatest progress has been achieved probably with the fuel, although even here the end has not been reached. It has been recognized that the knock tendency of gasolines could be substantially reduced by admixtures of benzol and alcohol; processes in gasoline refining have been perfected which assure more stable products, and the introduction of tetraethyl lead has lowered the knock tendency even more. As regards the mixture composition, the effect of the fuel-air ratio on knocking has been explored, and attempts have been made to raise the knock limitation by <u>stratified charging</u>.

The present report is confined to the effect of the combustion chamber shape on engine knock from three angles, namely:

1. The uniformity of flame-front movement as affected by chamber design and position of spark plug;

2. The speed of advance of the flame as affected by turbulence and vibrations;

3. The reaction processes in the residual charge as affected by the walls.

MANIFESTATION AND CONSEQUENCE OF KNOCKING

The explosive combustion of the residual charge excites the gas mass, which, in turn, induces the combustion-chamber walls to vibrations perceptible by ear as a ringing noise, detected by microphone or Midgley's bouncing pin.

The marked rise in the combustion rate at knocking must equally express itself in the pressure distribution. Unfortunately, the inception of the knock, i.e.: the instant of the change from normal to knocking combustion, is not very distinct on the pressure distribution, because by that time the expansion due to the piston motion is usually already superimposed on the pressure rise by the combustion. Through the formation of the first or second differential quotient of the pressure-time or pressure-piston path curve directly from measurement, the pressure change due to the knock inception can be more strongly expressed, although it should be remembered that this method indicates nothing not already contained in the pressure distribution record, even though less obviously. Since the pressure rise due to the knock moves through the gas mass at sonic velocity, the knock reading is subject to a certain phase difference and even damping, depending on the location of the test point. The measurement of the pressure vibrations induced by the knock and superimposed on the pressure distribution in amplitude and frequency by way of a special oscillation record amplification is, of course, also affected by the indicator orifice, the inertia of indicator and recording mechanism and the position of the test point.

Given identically responsive pick-ups, the method of vibration measurement is preferable, however, to the simple pressure recording method, as the amplitudes of a vibration can be much better followed than variations on a curve.

The rise of combustion rate in the residual charge following the knock has been proved by following the flame path with the ionization gap and slow motion pictures. Schnauffer, with ionization gaps fitted in the combustion chamber (fig. 1) proved that the flame speed of the non-detonating combustion in the engine amounts to only about 30 m/s, depending on the turbulence, but rises to 300 m/s and more at detonation (reference 2). (See fig. 2.) Rassweiler and Withrow obtained similar results (reference 3). (See fig. 3.)

The knock manifests itself in a reduced power output even if it starts after dead center where the approach to combustion at constant volume really should be followed by an improvement in power.

This decrease in power output is probably above all attributable to the increased wall losses, since the knock vibration speeds up the heat transfer from gass mass to wall quite considerably, and then also to the dispersion of energy resulting from the hammer-like stresses of the gears. The enhanced heat transfer at knocking and the rapid pressure rises induce higher mechanical and thermal stresses, which may cause rapid failure of the stressed components.

EXPLORATION OF THE KNOCK

There are two stages to be considered: First, the determination of the effect of outside conditions, namely, fuel, operating conditions (for instance, pressure and temperature of mixture, excess of air, compression ratio), and the combustion chamber design (its shape, position of spark plugs and valves, turbulence) on the appearance of the knock. The second stage concerns the processes in the residual charge itself during and shortly before combustion.

The explanation of the fact of knocking as of the explosive combustion of the residual charge seemed readily given: The fuel-air mixture is precompressed by the piston to a pressure and a temperature still at some distance from the conditions of auto-ignition. The ignition spark ignites the mixture next to the spark plug, produces a small flame nucleus which, through heat transfer onto the adjacent layers ignites these and so increases rapidly. As a result of the heat expansion of the burnt gas, the still unburnt mixture is compressed, its pressure and temperature rising through this compression, as well as through the radiation effect of the flame, and so altering its condition of igniting. In that way the auto-ignition limits can be exceeded, whence the rest of the charge then burns very suddenly without relation to the speed of flame motion conditioned by heat transfer and flow. The sudden combustion causes an abrupt pressure rise which moves as a pressure wave through the gas mass and on impinging at the cylinder walls produces a ringing noise: the knock.

THE PROCESS OF DISPLACEMENT

The actual speed of flame movement in closed containers consists - quite apart from the flow - of the ignition speed due to heat transfer and the speed of displacement due to the expansion of the burnt gas.

This process is illustrated in figure 4, and indicates the spread of a flame front in a spherical bomb with central ignition, the position of the flame front, and the movement of the individual gas layers represented by their radius r being computed from the pressure distribution as recorded by optical indicator. This calculation was carried out under certain simplifying assumptions such as heat impermeability of walls, constant specific heat, infinitely rapid balance of pressure rises over the chamber (reference 4). The radius r of a certain spherical layer is seen to increase so long as it has not been reached by the flame front. At the instant of passage of the flame front, the motion is reversed, because then the outer layers are subjected to heat expansion. The temperature rise of the unburnt gas as a result of the compression can be computed: Assuming heat-proof walls, it amounts to about 200° C. for the residual charge of the example in question. From the path of the flame front with respect to time, its speed can be deduced. The rate of displacement is highest at start of ignition, where the compression of the still huge unburnt part acts least against the expansion of the burnt part. The linear ignition speed increases with the temperature of the unburnt part rising with the progress of the combustion.

The effect of combustion chamber shape and spark plug setting on the rate of displacement and hence on the flame motion is readily apparent. To illustrate: Compare the flame movement in a cone ignited at the tip with that in a cylinder and assume identical ignition speed in both chambers, an assumption permissible when disregarding the wall effects and the flame front curvature on the propagation (fig. 5). Having covered half the cylinder or cone height, 50 percent is burned in the cylinder but only 1/8 of the content in the cone. Owing to the larger burnt volume, the flame front in the cylinder - under equal conditions - has therefore advanced farther than in the cone. For other reports on the displacement in dissimilar shapes, see reference 5.

On comparing the knock tendency of different combustion chamber forms with the rise in combustion speed due to displacement effect of the flame, it was found that the chambers with the lowest rate of displacement had the least tendency to knock. Accordingly, it was concluded that the knock depended on the rate of combustion of the part of the charge burning first, perhaps in such a manner that during the faster advance of the flame front the auto-ignition conditions of the residual charge are exceeded soonest, because it can then dissipate less heat.

This definition of the effect of combustion chamber shape on knocking as a result of a raised combustion speed does not hold under closer examination. Because, quite apart from the fact that many fuels (hydrogen) have less tendency to knock in spite of a high rate of combustion than others with lower rate of combustion, it still would be impossible to explain for instance why a mixture, ignited simultaneously at <u>several</u> spots, with much greater rate of combustion and hence rate of compression of unburnt gas has less tendency to knock than with ignition at one spot.

EXPLOSION WAVE

On igniting fuel-air mixtures in pipes, it may be observed that the propagation of the combustion rises to enormous speeds under certain circumstances. The resulting explosion wave, also termed detonation (identical with the so-called fire damp), differs from the normal flame movement due to heat transfer in the behavior of the burnt gas layers - the combustion gases - behind the flame front (reference 6). While in normal flame movement - amounting to a few meters per second at atmosphere pressure and temperature conditions for our fuel-air mixture without turbulence - the burnt gas layers have a motion opposite to that of the flame, the gas layers expanding as a result of combustion with the explosion wave push the flame front ahead of itself. The change from normal combustion to explosion wave is characterized by the fact that the combustion gases cannot flow from the flame front at arbitrary speed, thus stowing up pressure behind the flame front. This process, in constrast to the previously described displacer effect for which infinitely rapid pressure equalization was assumed, is not bound to closed chambers. The higher pressure speeds up the flame movement resulting, in turn, in greater pressure rise as a result of the combustion, until this is ultimately carried forward as a pressure wave with the sonic velocity corresponding to the state of the combustion gases - up to 3000 meters per second.

It suggested itself to associate the knock in the Otto engine indicated by a marked rise of combustion velocity with the explosion wave, and this process in the engine was actually termed at times "detonation." But closer investigation of engine knock and explosion waves have revealed the existence of fundamental dissimilarities between the two processes. The creation of an explosion wave is bound to pipes with minimum cross-sectional changes and to entrance lengths which do not prevail in the engine. The speed of propagation recorded in the knocking combustion (reference 2) is much lower than that of the explosion wave, the combustion at detonation does not start from the flame front but from auto-ignition nuclei in the residual charge (reference 3). Different fuels and additions to fuels react different to engine knock and to the explosion wave (reference 7). This dissimilar behavior is, according to our present state of knowledge, attributable to the advance reactions in the compressed mixture prior to the arrival of the flame front, whereas with the explosion wave no such advance reactions occur in the part of the mixture not yet reached by the flame front.

Since, in Germany, the term detonation is generally preferred for explosion wave and the knock in an engine is not synonymous with explosion wave, it would seem perhaps better not to use the word "detonation" for the concept of knock process in the Otto engine. When the Englishman uses the word "detonation" for "knock," he combines with it all rapidly occurring combustion phenomena in the sense in which we Germans use the word explosion.

KNOCK VIBRATIONS

While discussing the displacer effect, it was pointed out that the layers on passage of the flame front undergo a reversal of motion which incites the gas mass to vibrations. It was suspected and also proved that these vibrations, which are thrown back at the walls of the combustion chamber, increase in turn the rate of combustion and so can fluctuate between considerable values (reference 8). This combustion-induced vibration is illustrated by the oscillograms (in fig. 6), of the pressure variation at ignition of a fuel-air mixture in a cylindrical bomb, along with the superimposed vibration (reference 9). Such vibrations can equally be measured in the engine. The extent to which the rise in combustion speed caused by the vibration effects the knock in the engine, i.e., to what degree the vibration of the gas mass is in the main only the result of the knock and hence a criterion for it, is at present not amenable to conclusive appraisal.

Many phenomena observed in the exploration of the knock, particularly of the behavior of the different fuels and their influence by additions, point toward kinetics of reaction in the precompressed mixtures as the probable chief cause of the knock. But before proceeding with the discussion of these processes, we shall describe the practical results in the design of the combustion chamber which have proved suitable in the reduction of the knock inasmuch as this development preceded the research of the chemical-physical causes of engine knock.

COMBUSTION CHAMBER SHAPE AND KNOCK EXPERIMENTS

Ricardo was probably the first to make systematic tests of the effect of combustion chamber design on engine knock. His findings are briefly as follows (reference 10):

The path of the flame from the spark plug to the farthest corner of the combustion chamber should be as short as possible. The thus obtained short combustion period is important for the quality of combustion as well as for the knock; the most beneficial design from this point of view is the pent-roof type of cylinder chamber with the spark plug in the ridge of the roof, or else the disk type of chamber with horizontal valves (figs. 7 and 8). Corners remote from the spark plug in which the mixture becomes quiescent should be avoided. Since the actual rather than the relative flame path governs the knock, the larger cylinder of identical design and under identical operating conditions knocks before the small one, which latter can therefore be more highly compressed. But, on account of the higher heat losses in the smaller cylinder, the advantage of higher compression cancels as regards efficiency, thus making attainable indicated efficiency practically independent of the cylinder dimensions.

Asymmetrically mounted spark plugs lengthen the flame path, hence increase the knock tendency. Two or more spark plugs mounted so as to ignite the mixture at several points simultaneously lower the knock tendency very substantially, whereas the combustion approaching that of constant volume as a result of curtailed total combustion period, makes the use of several spark plugs a source of considerable power increase.

Relative to the length of flame path, the engine with laterally disposed valves is inferior to the head controlled. From a series of experiments, Ricardo believes to be able to conclude that turbulence of the charge reduces knocking. For laterally controlled engines, he suggests a "high turbulence head" with partly pulled-down combustion-chamber cover (fig. 9), which permits substantially higher compression than an evenly high disk type of chamber above the piston and the valves. The turbulence is created by the pressing of the mixture through the slot between cover and piston during compression.

Without abandoning his demand for minimum flame path length, Ricardo bases the design of the high turbulence head on the fact that the gap between piston and the pulled-down part of the cover should not be figured as "effective combustion chamber" - i.e., effective for knock - and he locates the spark plug in the center of the remaining effective chamber. The height of the gap remaining with piston at top center has, according to figure 10, a potent influence on the compression ratio permissible for knock-free operation.

Subsequent tests proved shifting of the spark plug toward the exhaust valve to be beneficial. For the four spark plug settings shown in figure 11, setting 1 affords a useful compression ratio of 5.87:1, as against 5.65:1 at setting 2, 5.3:1 at setting 3, and 5.45:1 at setting 4. Although the total flame path for setting 4 is more than 1.6 times as great as for setting 3, the former allows a considerably higher compression. It is therefore not only a matter of flame path length but equally also of the hottest part of the charge burning first, and the proper cooling of the part burned last.

One drawback of Ricardo's high turbulence head is its rough running, which is traceable to the excessive rate of combustion at the start of the combustion. This disadvantage disappears with the "shock-absorbing head" (fig. 12) on which the combustion-chamber cover above the exhaust valve is slightly pulled down also and the spark plug is mounted above the exhaust valve. This lowers the combustion rate shortly after ignition.

In partial contradiction with Ricardo, Whatmough's (references 11 and 12) points of view regarding combustion chamber design are as follows: The temperature of the total charge and especially that of the residual charge should be kept low, the length of the flame path is unimportant; turbulence should be avoided since then the temperature of the charge rises through absorption of heat from the hot walls. The "anti-turbulent" cylinder head based on these arguments, on which a very gradual transition of the combustion chamber in the cylinder is provided, is shown in figure 13. Janeway, among other researchers, holds that a vertical closing wall toward the gap is advantageous as it would produce a supplementary cooling of the residual charge on being pressed in the gap. Whatmough, holding the temperature of the mixture to be more important than the flame path demands first of all adequate cylinder-head cooling and avoidance of overheated spots in the combustion chamber. The spark plug in any case should be located near the hottest point of the chamber. In continuance of the tendency to cool the residual charge adequately, the same useful compression ratios were then subsequently obtained for laterally controlled engines as for top-controlled engines, on which a combustion chamber design with much shorter flame paths is possible. The fact that the pent-roof type of combustion chamber affords very high compression ratio with knock-free operation, is, according to Whatmough, due in part to the fact that during the exhaust cycle a protective gas cushion forms before the directly exposed head of the exhaust valve and so prevents its overheating (fig. 14).

The further development of the laterally controlled engine aims at the prevention of the discharge of hot combustion gases over the valve head and hence its overheating, so that the exhaust valve approaches the cover to within a small gap (fig. 15, left, top). To prevent the rapid flow over the head even when the valve is half open, the sidewall is pulled close to the valve seat (fig. 15, right, top) or recesses in the cover are provided into which the exhaust valve extends on opening (fig. 15, bottom) (reference 12).

The introduction of light alloys with their better heat conductivity as structural material for cylinder heads afforded a considerable increase in knock-free admissible compression ratio. To be sure, the enhanced efficiency is counteracted again by the higher heat losses. The use of light alloy or copper inserts in the combustion chamber at the points farthest from the spark plug increases, because of better cooling of the residual charge, the knock resistance, without the heat losses of the total charge becoming excessive. Cooling fins in the combustion chamber at the point of the last burning part of the charge are provided for the very same reason.

These practical findings summarily given here of the effect of combustion chamber shape on knocking which are in part contradictory (short flame path - flame path unimportant, turbulence knock reducing - turbulence knock increasing) and a number of other phenomena cannot be reconciled with the compression effect of the burnt on the unburnt gas nor with the explosion wave or the rate of combustion augmented by vibrations. The definition today is rather looked for in the reactions in the mixture to whose exploration the peculiar and in its causes largely unexplained behaviour of fuels under different conditions persistently furnishes the impetus. In order to gain a basic picture of these processes, we shall briefly discuss the chemical kinetics of the reactions in the gas phase as given in a speech by Professor Bodenstein and in a report by Professor Jost at the 1938 session of the VDI (references 13 and 14).

THE CHEMICAL-PHYSICAL PRINCIPLES OF KNOCK

The chemical kinetics are based on the kinetic gas theory, which, from an experiment of a simple comprehensive basic concept, has, through a multitude of experiments become a reliable description of the actual behaviour of gases. We know that gases consist of individual molecules in active motion within the space available. The motion of the individual molecules is unidirectional until collision with the walls of the container or with other molecules causes them to alter their speed and direction. They react normally as under completely elastic shock, i.e., they change speed and direction on attaining momentum and energy. But, under certain circumstances, these shocks cause the molecules to break up and the released atoms or groups of atoms to form other combinations.

THE SPEED OF REACTION OF THE HEAT EXPLOSION

The probability of collision of two types of molecules depends upon the number of molecules existent in the space and is, for a given spped, i.e., definite temperature, proportional to the product of the concentrations of the two substances; for which reasons the speed of reaction will be proportional to the product of the concentrations of the two constitutents so far as it does not take place over other intermediate members, as in the simplest case of bi-molecular reaction. At a certain temperature the mean speed is, to be sure, definitely defined from all molecules, but this speed is very non-uniformly distributed. The speed distribution follows a law of prababilityformulated mathematically by Maxwell. Only a very small fraction of the molecules, possessing a multiple of the mean motion energy is capable of reaction. According to the kinetic theory, the fraction μ of all molecules, which, reduced to one mole possesses the arbitrary energy q, is equal to

$$\mu = e^{-q/RT} \tag{1}$$

wherein R is the general gas constant and T the absolute temperature. On collision of the molecules of two different substances the bonds of the old atom combination must be substantially loosened in order to enter a new combination. The amount of energy required for this loosening is, referred to gram-molecule, equal to the so-called "heat of activation E kcal/mole," whence the number of shocks leading to a conversion should be proportional to

the factor $e^{-E/RT}$. Then the speed of reaction for the simple bi-molecular reaction may be written at

$$v = \frac{dn}{dt} = A\ e^{-E/RT} \tag{2}$$

where v is the speed of reaction, n the concentration of a product of reaction, and A a factor depending upon the concentrations of the components attaining reaction. In this formula, the unusually close relation between reaction speed and temperature is, if E at all assumes appreciable values, noteworthy.

If the re-bonding of the atoms occurs while the atoms are in a state of vibration which binds less energy than the old bond the reaction releases energy which on collision is transmitted to the other molecules and so raises their speed and temperature. This increment of speed, unless the temperature is lowered again by heat removal, enables more molecules to create activation energy, to react and in turn raise the temperature and speed of reaction.

With Q denoting the released heat of reaction per unit of change, the heat released per unit of time is

$$\frac{dq_1}{dt} = Q\ A\ e^{-E/RT} \tag{3}$$

Heat transfer on the walls of the container removes a quantity of heat proportional to the temperature difference between gas and wall, wall surface and a heat transfer factor which in first approximation may be considered constant for small ranges:

$$\frac{dq_2}{dt} = \alpha\ F\ (T - T_o) \tag{4}$$

According to the speed of the primary reaction and the heat transfer through the wall of the container the course of reaction may be divided into the three cases illustrated in figure 16, where the developed and evacuated heat volumes are plotted against temperature. If the heat development follows according to a temperature relation represented by curve c, temperature T_1 cannot be exceeded, as then more heat would be removed than produced (stationary reaction). Case b represents the unstable state of equilibrium at which for temperature T_2 the speed of reaction is invariable, if the effect of the consumption of the original product on the speed of reaction is disregarded. If the produced heat exceeds the removed heat a, explosion begins after a certain time lapse, the induction time, because temperature and speed of reaction rise mutually. The limiting condition for explosion is that for $T = T_2$ the developed heat is equal to the dissipated heat:

$$Q\ A\ e^{-E/RT_2} = \alpha\ F\ (T_2 - T_o) \tag{5}$$

Since the heat of activation E changes fairly little for a small temperature interval and A is dependent on the partial pressures of the components, the explosion conditions represent a relation between partial pressure, chamber temperature, wall area, and heat transfer coefficient.

In figure 17, where the speed of reaction is plotted against time, the lower curve indicates the stationary reaction, the middle one the extreme case and the upper one the explosion with the induction time τ. The induction time τ states that the speed of reaction approaches ∞ after this time lapse. Under simplifying assumption,

$$\tau \approx \frac{e^{+E/RT}}{p^a} \qquad (6)$$

can be derived for τ (references 14 and 16). It is pointed out as a result that the development of an explosion through auto-ignition processes takes a certain time the amount of which is primarily dependent upon the temperature conditions.

For the determination of this induction time τ with respect to different pressures and temperatures, there is a neat experimental layout built by Ricardo with which Tizard and Pye made their experiments on the auto-ignition of fuel-air mixtures (references 10 and 15). This experimental arrangement consists of a cylinder which is filled with the fuel-air mixture under definite, externally controlled conditions. A piston coupled only for the duration of this compression with a gear, compresses the mixture rapidly; after compression, the piston is held at the end of its upstroke. The pressure during compression and during the greater or lesser time lag of the auto-ignition is recorded by optical indicator. The most important results, in this connection of particular interest here, are the following:

1. Depending on the initial state and degree of compression induction times - i.e., time differences between piston at top center position and ignition - ranging from a few thousandths to several seconds were recorded;

2. The induction times yield a temperature relation according to an exponential function;

3. Several diagrams are shown on which at failure of the clamping mechanism the compression process was followed by expansion and a second compression. Although the pressure and temperature level had sunk considerably at the second compression as a result of heat losses, ignition took place within comparatively short induction times - figured from the second compression process (fig. 18).

Regarding these tests, it should be remembered that the compression initiated reactions which, after a certain time even without further action through radiation and the further compression of an advancing flame front, may induce ignition. It is in the nature of these processes that the primary reactions, which as yet scarcely effect the mean stage of the mixture and are therefore not identified with our mean state recording instruments, take the <u>longest time</u> (exponential function). But gradually these reactions circle in ever-increasing orbits and ultimately grow out in form of an avalanche to explosion.

So, whether or not the final mixture in the engine burns knocking or otherwise, will depend among other things, on the length of time it was left to itself after the precompression and so was able to get ready to explode. From this fact alone, that reactions already start under the influence of the compression - the pre-reaction - where it then depends, aside from the acceleration or delay due to heat input or removal, on the time interval up to the appearance of the flame front, of whether explosion takes place or not, effects of the combustion chamber on the knocking combustion can be more rationally explained than through displacer effect, explosion wave or combustion rate increase due to vibrations.

But it affords no summary explanation - without complicated assumptions concerning "ignition nuclei" in the mixture and an uneven temperature distribution maintained over a long time period - of the fact that the adiabatic pre-compression may, under certain circumstances, be accompanied by very long ignition lags with sinking pressure and temperature level during this lag. It also offers no explanation for the behavior of many fuels at different outside conditions and the effect of certain additions in small concentrations on engine knock. To explain these processes, it must be realized that the fuel molecule is a complicated chemical body whose reaction with oxygen must, to begin with, proceed in several stages and therefore cannot be exhaustively described through the process applicable in first instance only to bi-molecular reactions.

THE CHAIN EXPLOSION

If, as in the case analyzed so far, a rise in temperature is the cause of the rise in reaction speed, it concerns the so-called "heat explosion." Although every explosion in a certain stage changes to heat explosion, the temperature rise need not always be the primary cause. For a great many reactions the formation of "active" intermediate members is necessary. The so-called "chain reaction" is characterized by the fact that an active particle once formed releases a chemical change following which an active particle is again released. The free rather than the just-liberated atoms or groups of atoms are highly active, i.e., especially capable of reaction, as they possess freely a high energy as motion energy previously bound in the molecule as vibration energy. The reaction chain initiated by such an active particle may be protracted under certain circumstances. Reactions of this kind can be very strongly influenced by artificial production or destruction of active particles.

When an active particle leaves at the beginning two or more active particles at the end of the reaction it is called chain-branching. Through this process of chain-branching the speed of reaction can rise even without temperature increase to the extent that it is not prevented by chain-interrupting reactions. This rise in reaction speed through chain-branching can also lead to explosion. With this reaction process explosions, according to figure 18, starting at lower pressure and temperature level than the mixture had previously reached at any time, are explainable. Without knowing the mechanism of reaction in detail, it can be proved that the speed of reaction through chain-branching has a temperature relation conformable to an exponential function (reference 16). Since a chain interruption directly suppresses a great number of successive reactions, a very potent effect can be exercised by admixture of chain-interrupting substances in small quantities. The action of these substances, for which metallic oxides in molecular solution are best suited, is not to be understood as solely disactivating individual molecules with which they collide - i.e., destroy their energy lying above the intersection - as obtainable by adding rock dust to coal dust for the prevention of coal dust explosions - but as giving the reaction mechanism a different course through influencing the pre-reactions.

That the action of knock inhibitors in their effect rests on the pre-reactions initiated by the compression becomes evident from the fact that they have no influence on the explosion wave in pipes, during which process there is no time for pre-reactions in the unburnt part.

APPLICATION OF THE CONCEPTS OF KINETICS OF REACTION TO THE COMBUSTION OF THE RESIDUAL CHARGE

On re-examination of the mechanism of knock on the basis of this angle, enlarged with the help of chemical kinetics, it is seen that the effects on the residual charge, always in danger of a knocking combustion as a result of reactions released by the compression, are as follows (fig. 19):

1. Piston stroke: After top center it acts in direction of a pressure and temperature drop and so slows down the speed of reaction in the residual charge;

2. Expansion of burnt gas: It acts against the reduction of pressure due to the piston motion and should exceed it as a rule. The heat input from the approaching flame front through radiation on the mixture not directly at the flame front. Both accelerate the speed of reaction through pressure and temperature rise.

3. The heat produced by the reaction itself or by activation due to chain-branching - which causes a rise in temperature and through it of the speed of reaction in the residual charge. This effect is largely contingent upon the time lapse between compression and arrival of flame front;

4. Heat removal (or heat input) due to heat transfer to the walls. In a given case, chain interruption through the walls and consequently reduction in speed of reaction.

Qualitatively, the effect of form of combustion chamber, spark plug setting, turbulence and walls may according to the foregoing be appraised as follows:

A long flame path, i.e., great distance of the corners of the combustion chamber farthest away from the spark plug increases, with the time period during which the residual charge is left to itself after compression, the probability of the reactions terminating in explosion. A residual charge at great distance from the spark plug is harmless so long as it is deprived of heat of compression and heat of pre-reaction.

By raising the combustion rate, whether through displacer effect, turbulence, or vibration, the auto-ignition process on one side in the residual charge is overtaken sooner by the flame front and the knock tendency thus reduced, while on the other side the accelerated compression lowers the heat removal from the residual charge. Whichever effect predominates depends upon the wall temperatures and the stage of auto-ignition process. As a rule, however, the knock is less apt to occur in accelerated combustion, as seen for instance from the effect of the r.p.m. on the knock, and the use of several spark plugs.

Turbulence increases the combustion speed as well as the heat transfer. If the wall temperatures are lower than those of the residual charge, turbulence acts to reduce knock, otherwise to increase knock. The lower the wall temperatures are, the less the knock tendency will be. The extent to which knock can be reduced say, through non-partitioned combustion chamber form and avoidance of hot exhaust valve, for instance, is readily apparent from the high knock resistance of the sleeve-valve engine.

The reason for our inability to give a quantitative appraisal of these effects rests in our lack of insight into the mechanism of reaction accompanying the combustion of hydrocarbons and on our insufficient knowledge of the heat transfer during rapidly changing processes. The boundary of the residual charge is formed by partly hotter, partly cooler combustion-chamber walls and by a hot flame front. Here, it is at present impossible to give even only approximately correct information about the heat exchange of the residual charge with its boundary surfaces due to heat conduction influenced by turbulence, as well as through the radiation of the individual gas layers through the others, nor through the energy transferred direct to the walls by pressure waves.

SUMMARY

It is the function of every theory to classify experiences in a uniform pattern, so as to enable predictions to be made on the basis of this standard. A theory is correct so long as it is not refuted by experiance. If, with a limited amount of experience, several non-contradictory interpretations are feasible, the simpler one is the best.

As regards the process of knock, we are aware that, especially relative to the behavior of fuels, to the mechanism of reactions over the different intermediate components, and to the correct interpretation of many phenomena as cause or effect, our state of knowledge presents many gaps. But even so, it appears that on the basis of the theory of the automatically occurring reactions in the fuel-air mixture, the most uniform and simplest interpretation of the effect of combustion chamber on engine knock is possible, wherein displacer effect, explosion wave, and increase of combustion due to vibrations will play, at the most, secondary part.

Translation by J. Vanier,
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for Aeronautics.

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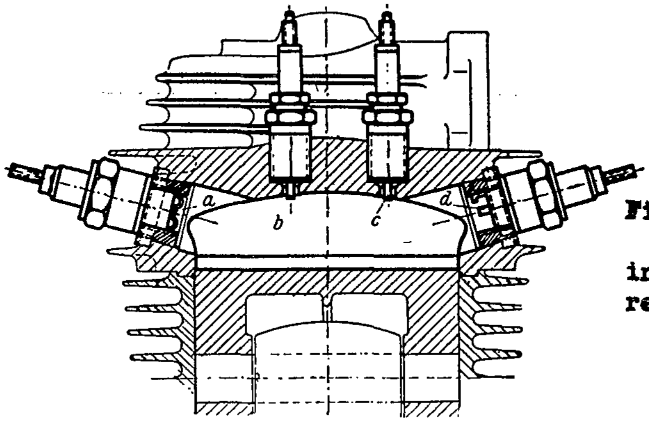


Figure 1.- Arrangement of ionization test lengths in cylinder head for flame speed recording.

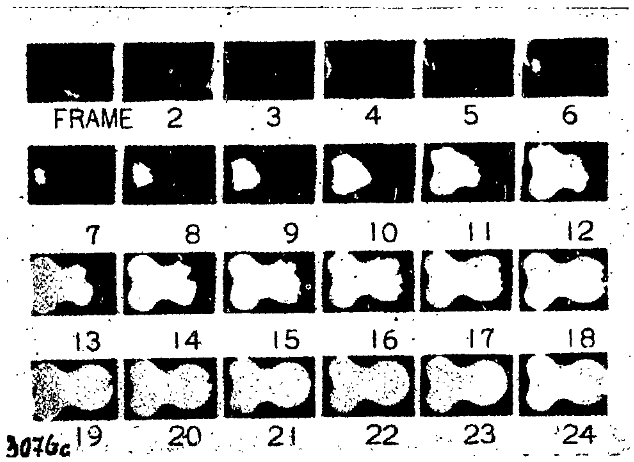


Figure 3.- Engine flames in normal combustion (Rassweiler and Withrow).

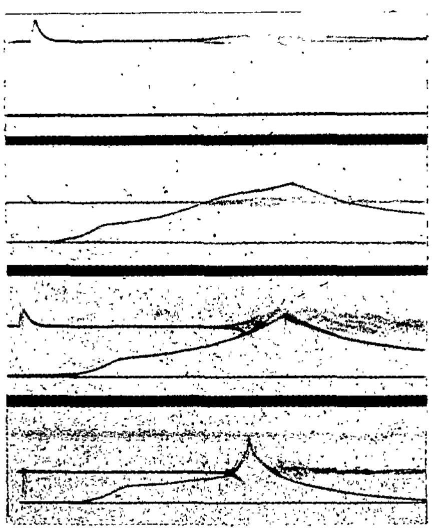


Figure 6.- Formation of knock vibration.

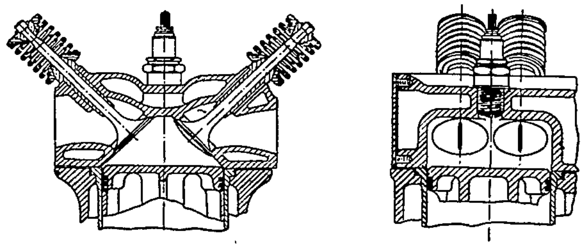


Figure 7.- Pent-roof type of combustion chamber with overhead valves (Ricardo).

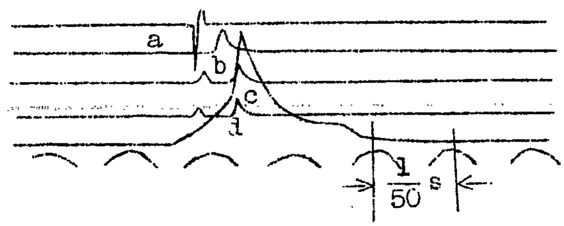


Figure 2.- Oscillogram with pressure distribution in cylinder and marking of arrival of flame at the test point.

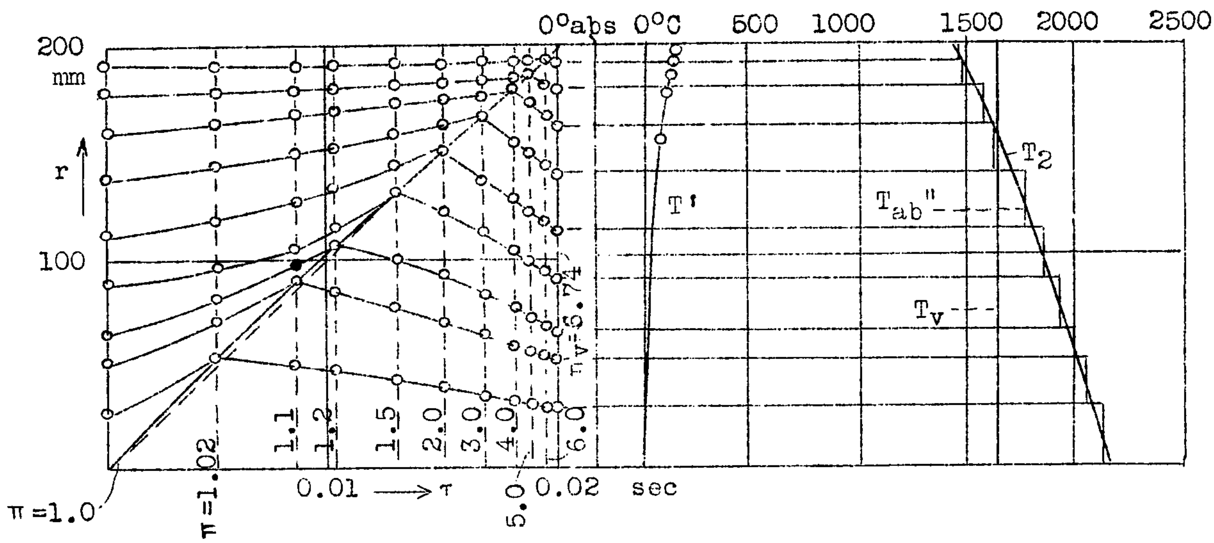


Figure 4.- Time lapse of combustion process (Nägel).

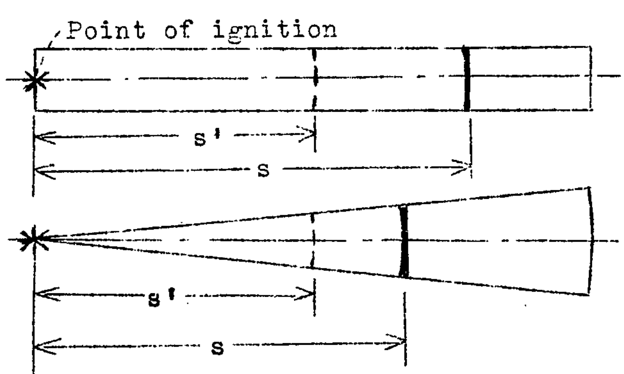


Figure 5.- Linear (s') and of linear and displacement built up flame propagation (s).

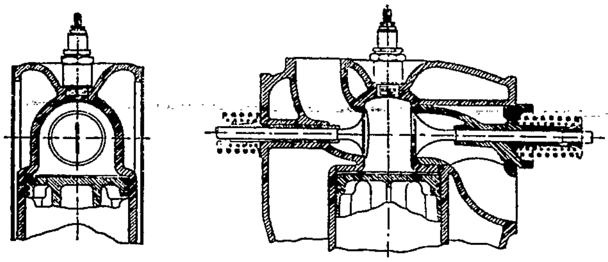


Figure 8.- Combustion chamber with opposite horizontal valves (Ricardo).

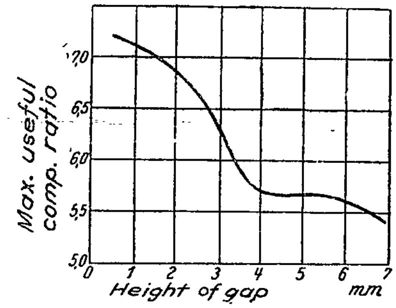


Figure 10.- Relation of knock-free useful compression ratio to height of gaps.

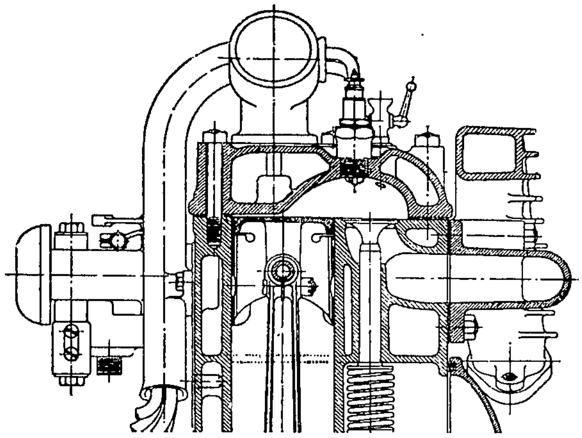


Figure 9.- Ricardo type head for laterally controlled engines.

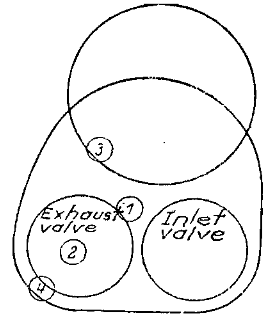


Figure 11.- Different spark plug settings in Ricardo's head.

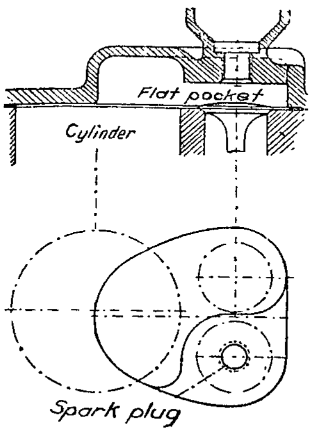


Figure 12.- Cylinder head with shock absorption (Ricardo).

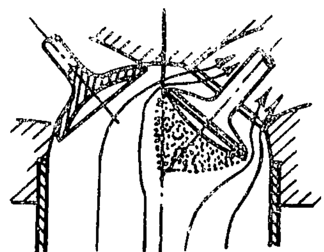


Figure 14.- Whatmough's gas cushion before the exhaust valve.

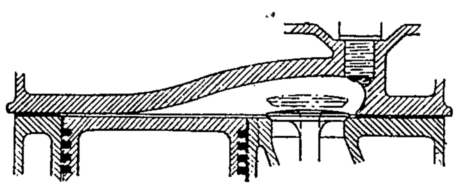


Figure 13.- Whatmough's anti-turbulent cylinder head.

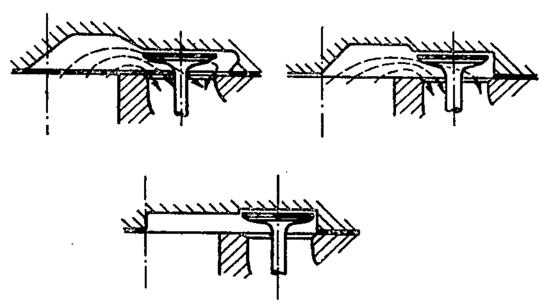
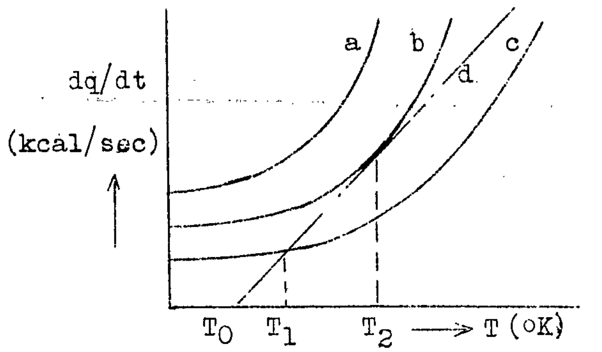


Figure 15.- Combustion chamber shapes of laterally controlled engines.



Curves a,b,c: heat dq_1/dt developed in unit time by chemical conversion.
Curve d: heat dq_2/dt transferred to wall in unit time.
Figure 16.- Heat explosion according to Semenoff.

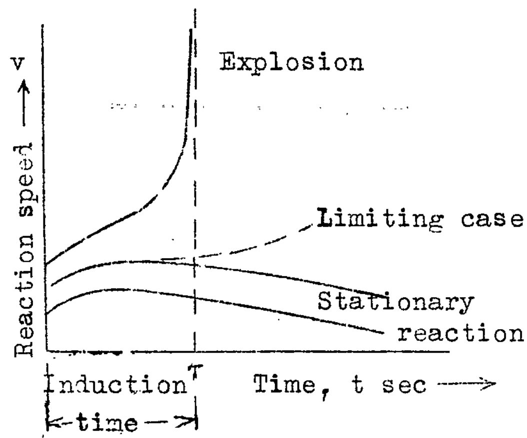


Figure 17.- Time rate of change of reaction speed for an explosion.

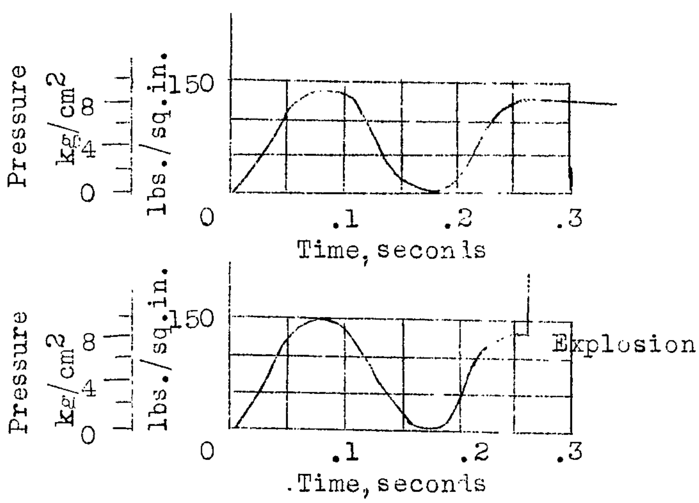


Figure 18.- Pressure distribution during adiabatic compression.

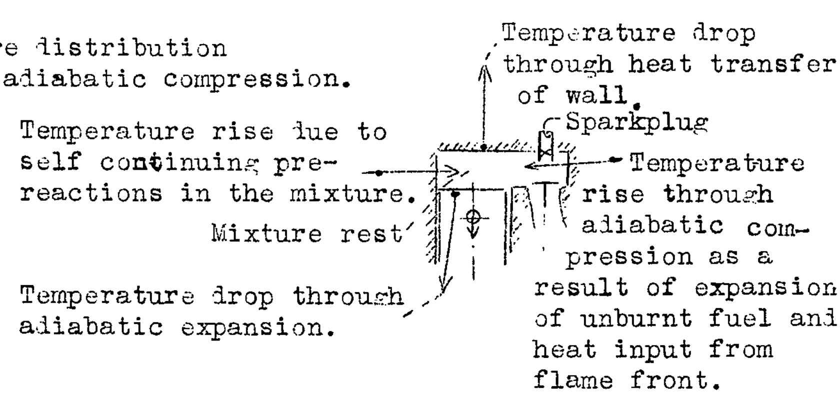


Figure 19.- Influence of temperature of residual charge and time of the speed of reaction.